DESIGN AND VERIFICATION OF VERTICAL AXIS WIND TURBINE SIMULATION MODEL

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Abstract. In the course of this research the vertical axis wind turbine simulation model has been designed and verified using the MATLAB SIMULINK tool for transient process simulation. The research was based on the study of the real vertical axis wind turbine, which provided the basis for building the mathematical model. The mathematical model includes the mechanical model of the turbine, wind, turbine rotor, power output and all rotation parameter analysis and calculations. The main goal of the research was achieved and the designed model was successfully verified by the real turbine performance data. The results showed that the error of the modelled data and the real turbine data is less that 2 %, which provides an opportunity to use this model for subsequent research and turbine production or R&D in the future.

Key words: wind turbine, open access transfer function, simulation, torque, moment of inertia.

Introduction

Use of the renewable power resources has been the subject of active discussions and research for many years already. Exorbitant amounts have been invested to research this area aiming to find the possibility to gain high quality power from renewable energy resources (biomass, sun, wind) with a high degree of efficiency. Optimisation of the performance factor in energy generation and use remains a compelling and as yet unresolved issue in modern power production systems, the same being true for the renewable power industry [1].

The most important role in speeding-up the progress in the development of the new technologies belongs to computer model based engineering of equipment and process simulation, which provides an opportunity to test the new ideas, methods and strategic solutions and to obtain quick and accurate results without the necessity to spend considerable amounts on acquisition and installation of experimental equipment [2]. At present, a lot of various simulations are done in connection with wind power engineering. Certain models for low, medium and high capacity wind equipment and its separate elements have been developed and studied. However, the evaluation and optimisation of the quality of operation of the management systems that link together the wind power engineering equipment and energy consumers lacks a proper systemic approach that would help stitch together into one system virtual models, analog models and real-life technological equipment.

If we take wind power engineering – any system here is pretty complicated for the set of its parameters being described merely by means of simple algebraic equation, which suggests that the only way how to simulate the processes occurring within the system and analyse the obtained results both in digital and graphical format is to apply the real-time simulation method [3].

By analysing the exploratory work done in the area of simulation of mechanical stages of a wind station – blades, rotor, reducer, it may be concluded that in the majority of cases the simulation models of that stage are being simplified, which gives a generalised representation of the wind energy transformation process patterns while a lot of important aspects are disregarded and, as a result, the model fails to properly reflect the actual processes. The present research improves the traditional models by assessing the parameters determinative for dynamic transformation processes in wind turbine operation [4].

Materials and Methods

In June 2012, in Talsi the experimental research of the patented [5] vertical axis wind turbine was performed (Fig. 1). According to the specification, the turbine capacity range is 0-23 kW, the angular speed of the shaft rotation is 3-9 rad$\cdot$s^{-1}, optimal tip speed ratio 1.1, the turbine is equipped with a 12-pole magnetic pulse synchronous generator with the synchronous rotation speed of 18 rad$\cdot$s^{-1} and the nominal capacity of 25 kW.

The experimental data for the turbine were recorded by using the automatic recorder registering step of 1 s. Data recording was conducted continuously. For development of the simulation model and comparison of the obtained data a 3500 s interval was chosen from the recorded set of data. The following data recordings were used: wind speed, angular speed of the shaft rotation, active electric capacity of the generator output and tip speed ratio. On the basis of the recorded data the wind turbine simulation model was developed in the MATLAB SIMULINK environment.

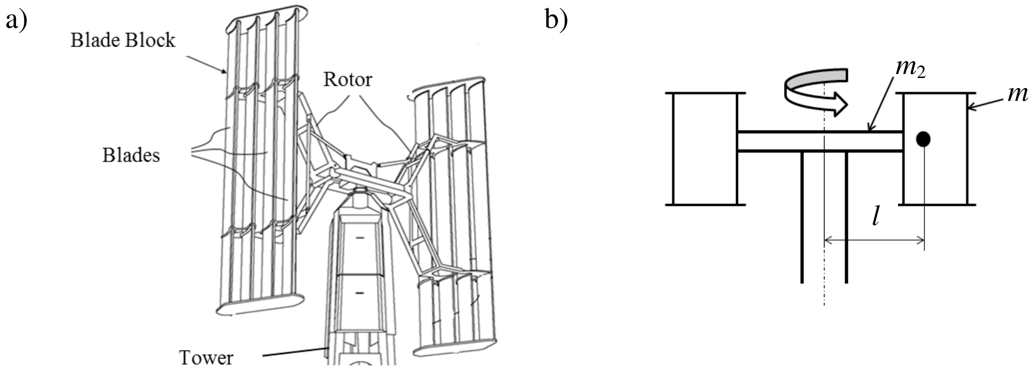

Fig. 1. **Wind turbine mechanical design according to the patent [5]:** a – full structure; b – simplified structure for calculation of the moment of inertia (m_1 – blade block mass, kg; m_2 – rotor mass, kg; l – radius of mass centre).

Table 1 contains the list of the equipment that was used for recording and measuring the experimental data.

Table 1

Recording and measuring equipment

Name	Measured data	Units
RSI503	Turbine angular speed – ω	$rad \cdot s^{-1}$
Integra 1630	Turbine active power – P	kW
WXT520	Ultrasonic weather station, wind speed – V	$m \cdot s^{-1}$
PM573-ETH	Data registration system (system time, turbine angular speed, turbine active power, wind speed)	1 $record \cdot s^{-1}$

The wind turbine shaft rotational torque M_{wind} depends on the four major parameters. It is directly proportional to the wind velocity V cube multiplied by the turbine efficiency η and the turbine rotor radius ($R \cdot L$), and inversely proportional to the angular speed ω. The speed of wind is the most important parameter. The wind turbine shaft rotational torque can be calculated by help of the following expression [6]:

$$M_{wind} = \frac{\rho \cdot R \cdot L \cdot \eta \cdot V^3}{2 \cdot \omega}, \tag{1}$$

where M_{wind} – wind turbine torque, Nm;
V – wind speed, $m \cdot s^{-1}$;
$L = 7.5$ – length of the blades, m;
$R = 3.75$ m – wind turbine rotor radius;
$\rho = 1.225$ $kg \cdot m^{-3}$ – air density;
$\eta = 0.275$ – wind turbine efficiency.

In the process of simulation, the dynamic behaviour of the wind turbine is one of the most important factors that determines the time and speed of the wind turbine transfer process. The transfer process occurring in the wind turbine is described by the following algorithms:

$$T \frac{d\omega}{dt} + \omega = K \cdot V, \quad T \cdot \omega(s) \cdot S + \omega(s) = K \cdot V(s), \quad W(s) = \frac{\omega(s)}{V(s)} = \frac{K}{T \cdot s + 1}, \tag{2}$$

where T – time constant of the wind turbine inertia, s;
$K = \omega_{nom}/V_{nom} = 0.26$ $rad \cdot m^{-1}$ – transfer coefficient of the wind turbine system;
$\omega(s)$ – Laplace transform of the turbine shaft angular speed, $rad \cdot s^{-1}$;

$V(s)$ – Laplace transform of the wind speed, m·s^{-1};
$W(s)$ – transfer function of the wind turbine;
s – Laplace variable, s^{-1}.

One of the most important parameters describing the dynamic behaviour of the wind turbine is the moment of inertia J, which is calculated as an approximation due to structural complexity:

$$J = 2 \cdot \frac{m_1 \cdot \frac{m_2}{2}}{m_1 + \frac{m_2}{2}} \cdot l^2 = 2 \cdot \frac{320 \cdot \frac{1100}{2}}{320 + \frac{1100}{2}} \cdot 2.5^2 = 2528\ \text{kg}\cdot\text{m}^2\ , \tag{3}$$

where m_1 = 320 kg – block mass of the wind turbine blades;
m_2 = 1100 kg – wind turbine rotor mass;
l = 2.5 m – radius of mass centre.

The time constant of the turbine transfer process can be calculated by help of the following expression:

$$T = \frac{J \cdot \omega}{M_{wind} - M_{load}}\ , \tag{4}$$

where ω – wind turbine angular speed, rad·s^{-1};
M_{load} – load torque, Nm;
J – wind turbine moment of inertia, kg·m^2.

The turbine load torque is calculated by help of the following expression:

$$M_{load} = \frac{\pi \cdot \rho \cdot R^5 \cdot \eta}{2 \cdot \lambda^3} \omega^2\ , \tag{5}$$

where $\lambda = \omega \cdot R/V$– tip speed ratio.

Aerodynamic efficiency of the wind turbine is dependent upon the relation between the tangential speed of the tip of a blade and the actual speed of the wind expressed as the tip speed ratio – λ. For the experimental wind turbine the value of λ = 1.1. Any deviation from the most efficient speed relation results in decrease of the efficiency ratio.

The model that was built in the MATLAB SIMULINK environment consists of 6 subsystems. The turbine model includes simulation of the wind parameters, simulation of the turbine torque induced by variable wind vectors, simulation of the mechanical transfer process, calculation of the turbine kinematic parameters and data comparison (Fig. 2).

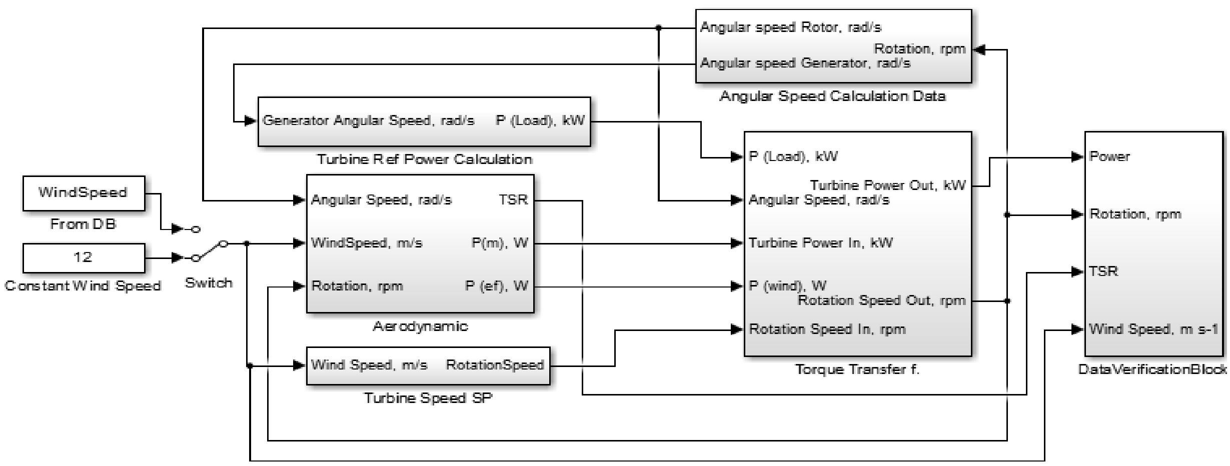

Fig. 2. V**irtual model of the wind turbine in MATLAB SIMULINK**

The wind induced power simulation structure is included in the "Aerodynamic" subsystem, where, depending on the technical parameters of the turbine, the wind-generated torque is calculated and is simulated within a specific time period (Fig. 3). The representative curve of the simulated wind torque is a non-sinusoidal function that demonstrates how the turbine torque is changing within one rotation time. The form of the representative curve changes depending on the aerodynamic coefficients.

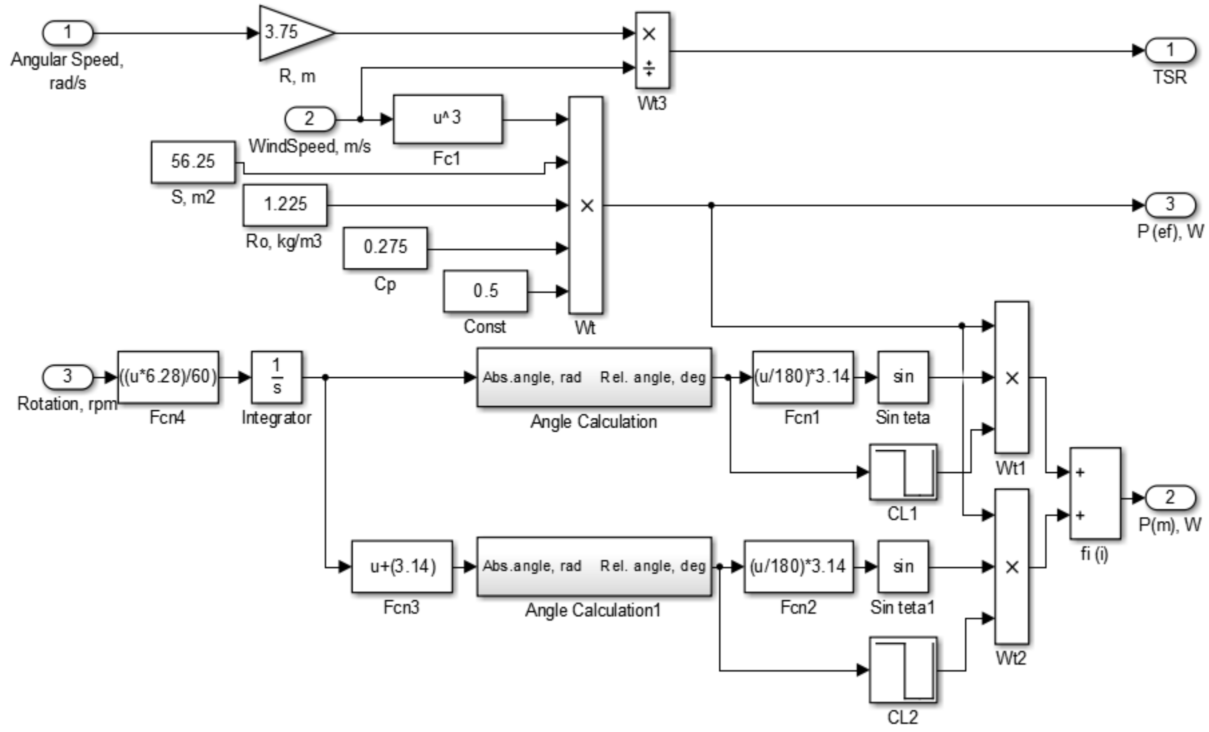

Fig. 3. **Virtual model of the wind generated torque of the turbine**

The wind turbine transfer process is related to the transmission of wind energy. This process of transfer is simulated in the "Torque Transfer f." subsystem , which includes recalculation of the turbine time constant T depending on the turbine moment of inertia J, wind reduced torque M_{wind}, load torque M_{load} and the wind turbine angular speed ω, which is the subsystem output value (Fig. 4).

For recalculation of the time constant a free access transfer function model has been created by means of an integrator with the negative unit feedback loop, which makes it possible to recalculate the turbine time constant for the duration of the process of simulation [7]

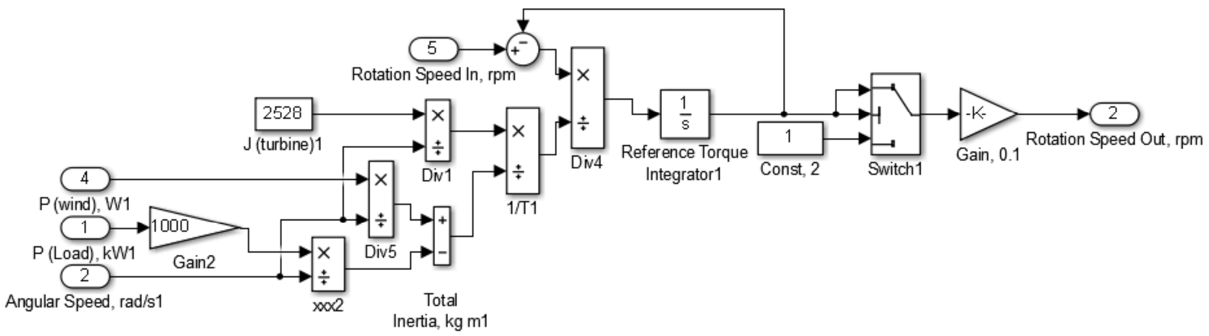

Fig. 4. **Subsystem model of the wind turbine transfer process simulation**

Results and discussions

The output of the wind turbine simulation model was compared to the data recorded in the course of the experiments with the recording step – 1 second. The simulation step was set at 0.001s. The data gained during simulation were compared to the experimental data by recording these in the graphic recorder. The simulation output data – the turbine angular speed ω, load torque M_{load} and tip speed ratio λ, were compared to the values recorded in the course of the experiment.

The experimental data – the characteristic curve V_{exp} of wind speed $V(t)$ as well as the characteristic curve showing the wind turbine angular speed ω_{exp} and the characteristic curve of simulation data ω_{sim} are presented in Fig. 5. The wind speed V oscillates about the average value 5 m·s^{-1} and stochastically alternating breeze with the amplitude ±1 m·s^{-1} and the changing frequency of oscillation.

The characteristic curve of the turbine angular speed ω_{exp} demonstrates that the main component is being superimposed by high-frequency components, which suggests presence of high-frequency vibrations caused by blade deformation and non-uniform rotation of the turbine – the effect produced by alternating wind. The characteristic curve of the turbine angular speed ω_{sim} shows a good fit with the main component of the experiment characteristic curve. In this case, simulation of high frequency oscillation in the model was not anticipated because it has immaterial effect on the wind turbine shaft torque, which is stabilised by the turbine inertia and load.

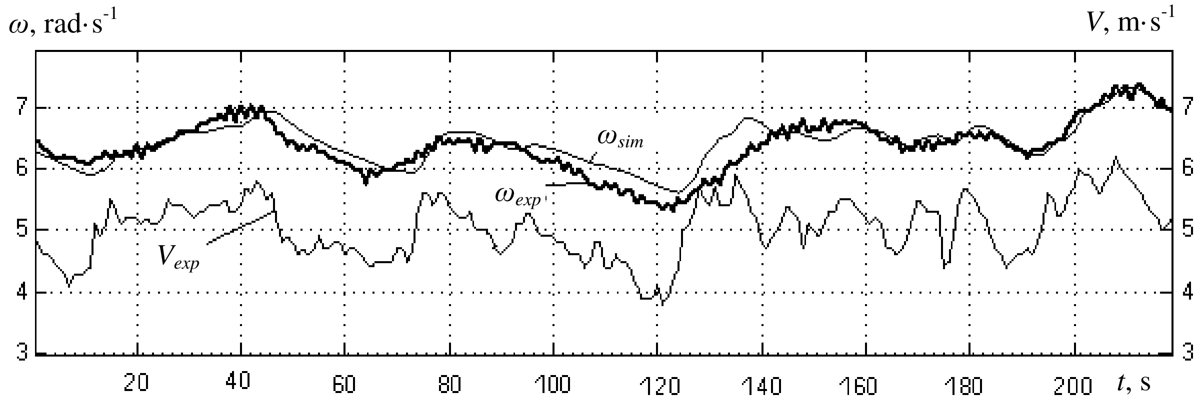

Fig. 5. **Characteristic curves of the wind turbine angular speed $\omega(t)$ and wind speed $V(t)$:** ω_{sim} – simulation; ω_{exp}, V_{exp} – experiment

According to the experimental and simulation data shown in Fig. 6, the tip speed ratio – λ proves that regulating algorithm of the experimental turbine does not ensure the specified $\lambda = 1.1$. The figure demonstrated a good fit of the experimental data and simulation data. During simulation λ is controlled by the same regulating algorithm that was used in the experimental turbine, which explains why deviation from the specified value is similar in both cases.

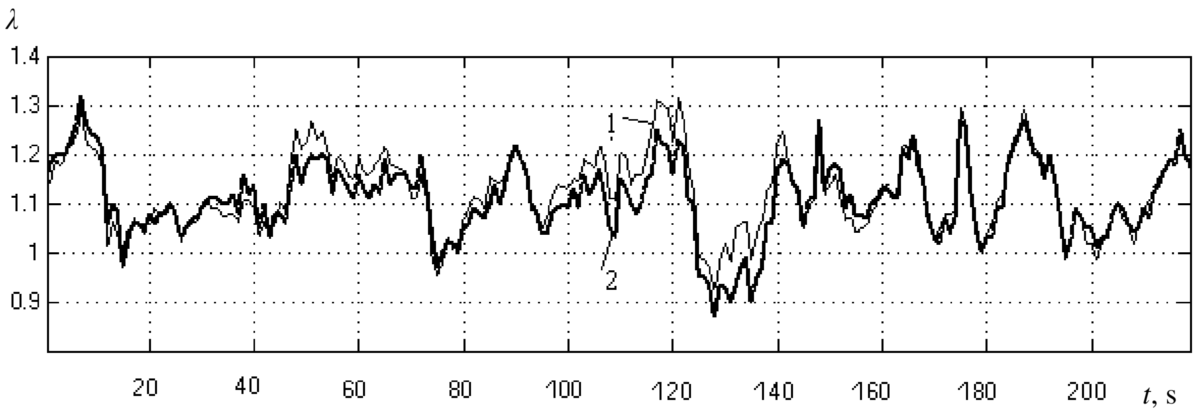

Fig.6. **Characteristic curves of the wind turbine tip speed ratio $\lambda(t)$:** 1 – simulation; 2 – experiment

During simulation the data about λ with the average value of 1.1 were gained, however, in the course of simulation a slight bias is observed, with the average variance ±0.1. During simulation the divergence of λ was observed within the range from 100 s to 120 s, which sometimes reaches the value of ±0.2. This is explained by significant change of the wind speed. The turbine real moment of inertia J differs from the calculated value, which explains the difference between the experimental and simulation data observed in certain cases.

Conclusions

1. The wind turbine is a non-stationary inertial dynamic object, therefore, for simulation of its transfer processes in the MATLAB SIMULINK environment it is required to apply a free access transfer function by using an integrator with the negative unit feedback loop, which makes it possible during simulation of the transfer process to automatically adjust the time constant of the turbine model and significantly improves the simulation accuracy.
2. The virtual model of the wind turbine with the free access transfer function allows free communication with the body of numerical data representing experimental measurements of wind parameters by feeding these data into the model, therefore, the suggested model uses the physical measurements of the real wind rather than taken from an artificially drawn wind characteristic curve.
3. The characteristic curve of the turbine angular speed ω_{exp} shows that the main component is being superimposed by high-frequency components, caused by blade deformations and non-uniform rotation of the turbine – the effect produced by the alternating wind flow. The model does not provide for simulation of the high-frequency oscillation of the rotation speed because it has immaterial effect on the wind turbine shaft torque, which is stabilised by the turbine moment of inertia and load.
4. The data of the turbine tip speed ratio λ gained during the experiment and as a result of simulation demonstrate a bias from the specified value 1.1, with the average deviation amplitude ±10 %, in certain cases reaching the maximum deviation amplitude of up to ±20 %, caused by the high-frequency wind speed fluctuations.

References

1. Bati A. F., Brennan F. The Modelling, Simulation and Control of a 50 kW Vertical Axis Wind Turbine. Asian Transactions on Engineering, vol.2, No.4, 2012, pp.14-24.
2. Ran L., Rumby J.R., Tavner. P.J.I. Use of Turbine Inertia for Power Smoothing of Wind Turbines with a DFIG. Proceedings of International conference “11th International Conference on Harmonics and Quality of Power”, September 12-15, 2004, pp. 106-111.
3. Thakur T., Gupta S.K. Modelling of a Stand-Alone Induction Generator on Load Using MATLAB SIMULINK. Journal of Emerging Trends in Engineering and Applied Sciences, vol. 3, 2012, pp. 729-733.
4. Bharanikumar R., Yazhini A.C., Nirmal Kumar A. Modelling and Simulation of Wind Turbine Driven Permanent Magnet Generator with New MPPT Algorithm. Asian Power Electronics Journal, vol.4, No.2, 2010, pp. 52-58.
5. Krishna S.B., Reeba S.V. Control of permanent magnet synchronous generator wind turbine for stand-alone system using fuzzy logic. Proceedings of International conference “10th National Conference on Technological Trends”, November 6-7, 2009, pp. 106-111.
6. Scerbina A. Vertical axis rotor-type wind turbine/ US Patent Nr. 8,226,348/415/42; 415/44; 415/907; 416/111. Feb. 5, 2009. Available at http://www.google.com/patents/US8226348
7. Sniders A., Straume I. Simulation of electrical machine system with permanent magnet synchronous generator. Proceedings of International conference “Engineering for Rural Development”, May 29-30, 2008, Jelgava, Latvia, pp. 97-102.